

Developing New Low-Temperature Admixtures for Concrete

A Field Evaluation

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Abstract: Two new admixtures, capable of preventing water from freezing, as well as increasing the hydration rate of cement at below-freezing temperatures, were field tested at Sault Ste. Marie, Michigan. Concrete made with the admixtures was placed on a frozen subgrade during a cold winter day and was al-

lowed to cure thermally, unprotected in the cold. Comparison to control concrete placed inside a heated shelter showed that the unprotected, admixed concrete was equal to the control in strength and appearance. Work is continuing on the development of these admixtures for commercial use.

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PREFACE

This report was prepared by Charles Korhonen, Research Civil Engineer, Brian Charest, Research Civil Engineer, of the Civil and Geotechnical Engineering Division, Research and Engineering Directorate, U.S. Army Cold Regions Research and Engineering Laboratory; and Kurt Romisch, Chief, SYM Shops, Yards and Mechanical Branch, Soo Area Office, U.S. Army Engineer District, Detroit. The investigation was conducted under the authority of the Corps Construction Productivity Advance Research (CPAR) program.

The authors acknowledge the support of Stanley Jacek, Area Engineer, Soo Area Office, as well as of the work crew from the Soo that placed the concrete. Technical review was provided by William F. Quinn (CRREL) and John W. Brook (Master Builders, Inc., Cleveland, Ohio).

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Developing New Low-Temperature Admixtures for Concrete

A Field Evaluation

CHARLES KORHONEN, BRIAN CHAREST, AND KURT ROMISCH

INTRODUCTION

During March 1994, an innovative way of protecting fresh concrete from freezing was field tested in northern Michigan at the Soo Locks in Sault Ste. Marie (run by the U.S. Army Engineer District, Detroit). Instead of using the customary insulation or heated enclosures, special chemical compounds were added to the concrete to help it gain strength while its internal temperature was below the freezing point of water. Two prototype chemical formulations, antifreeze admixtures, were developed as part of the Corps Construction Productivity Advancement Research (CPAR) program. This field test intentionally allowed fresh concrete to cool below freezing without any attempt being made to insulate or heat it.

BACKGROUND

Construction Productivity Advancement Research (CPAR) program

CPAR allows Corps research laboratories, such as CRREL, to work with private industry on Research and Development that has potential for advancing the art of construction and for being of value to Corps activities. The intent of CPAR is to catalyze improved construction technology through cooperative, cost-shared ventures. Such a venture resulted in the development of the two admixtures described in this report.

These admixtures were developed under two independent projects—Master Builders, Inc., and W.R. Grace & Co. entered into separate contracts with CRREL in 1991. Each project was successful in bringing a practical antifreeze admixture to the threshold of commercialization.

Conventional practice

Current winter concreting practices have remained unchanged for many years. Concrete ingredients must be heated to melt all ice and to create a mix temperature that is well above freezing; the substrate on which fresh concrete is placed must be thawed; and the concrete must be kept warm and moist long enough to assure adequate strength.

Construction standards require that normal concrete be kept at or above 5°C (ACI 1988) until it has cured. As temperatures drop to this mark, finishing operations take longer and forms cannot be stripped as fast as they can during the summer. The strength gain of concrete is slowed. At a few degrees below zero, not only is the hydration rate of cement slow, the mix water begins to turn into ice. At -3°C, 90% of the water will freeze (Korhonen 1990). If freezing occurs, the concrete may lose half its strength. Figure 1 shows the effect of temperature on the strength of normal concrete.

Freezing, however, is a threat for only a short time. As concrete matures and water chemically combines with cement, the quantity of freezable water diminishes to the point that freezing the concrete once will not damage it. Most concrete develops this level of self-protection by the time it reaches a compressive strength of 3.5 MPa (ACI 1988), which, for normal concrete cured at 10°C, can happen in a day.

The procedures used today to protect concrete from freezing and to assure adequate strength do produce concrete that meets construction needs for strength and durability. However, this protection can be expensive. It has been estimated that the U.S. construction industry spends \$800 mil-

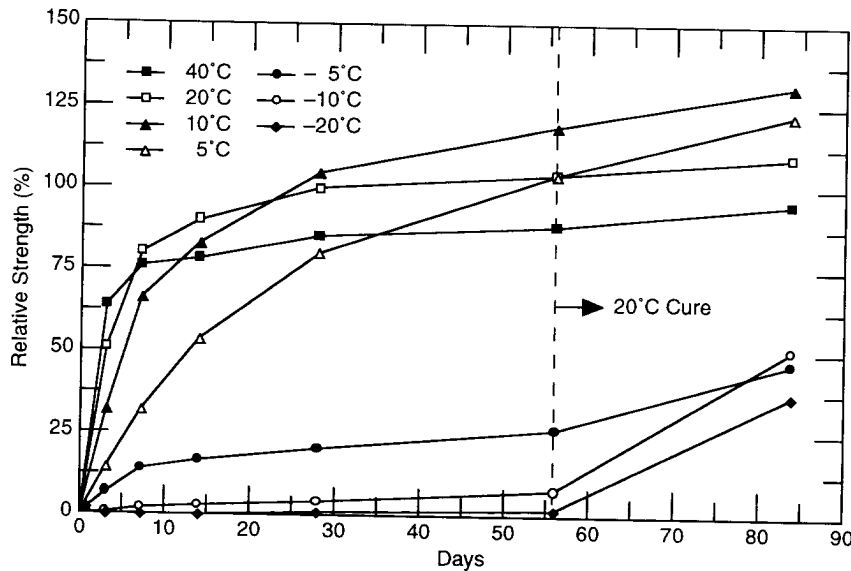


Figure 1. Effect of temperature on strength gain of normal concrete. All strengths are referenced to the 28-day strength of the 20°C concrete. The 40, 10 and 5°C lines are based on relations presented by ACI. The other data are from laboratory tests at CRREL.

lion every year on measures to protect fresh concrete from freezing (*Civil Engineering* 1991).

Antifreeze admixtures

Antifreeze admixtures are chemicals that depress the freezing point of water and accelerate the hydration of cement. The literature cites numerous chemicals that can function as accelerators, calcium chloride being the most popular. And there are many common substances that dissolve in water and can serve as freezing point depressants. The challenge, however, is to find chemicals that will work together and that will not harm the concrete.

Because no standards or acceptance criteria are available for antifreeze admixtures, it was necessary at the start of the CPAR projects to define such criteria. An antifreeze admixture should:

- Depress the freezing point of water.
- Promote strength gain of concrete at low temperatures.
- Not interfere with concrete strength gain at normal temperatures.
- Maintain the workability of the concrete.
- Achieve a reasonable concrete set time.
- Produce freeze-thaw durable concrete.
- Not react with silica aggregate.
- Not corrode steel.
- Not adversely alter hydration products.
- Be cost effective.

Also, we decided that the initial low-temperature goal would be -5°C , with -10°C or perhaps -20°C being the ultimate objective, and that the concrete cured at this low temperature should gain strength at least as rapidly as normal concrete cured at 5°C .

Numerous chemical mixtures were investigated before one prototype formulation from each company was selected for final testing: EY11 from Master Builders, Inc., and DP from W.R. Grace & Co. Because the admixtures are proprietary, the chemicals used in them are not disclosed.

Data from nearly two years of laboratory testing have not proven that the prototype admixtures harm the concrete. The concrete made with each admixture passed standard freeze-thaw tests, did not shrink excessively, did not contain excess alkalis, and did not promote corrosion. Further, the admixtures promoted strength in concrete cured at -5°C that exceeded the strength attained by normal concrete cured at 5°C . The prototypes were ready for field evaluation.

FIELD EVALUATION

Soo Locks

The Soo Area Office was replacing 39 sections of concrete that showed advanced freeze-thaw deterioration. They devoted four reinforced slabs on grade, measuring 5.5 m wide by 6.1 m

long by 15 cm thick, to the experiment; they were cast on 15 through 17 March. Inspection and repair of the locks and other repair work, such as the replacement of these slabs, is most conveniently done during the winter, after the shipping season, making this test particularly relevant.

Site preparation

The site was prepared by jackhammering out alternate sections of concrete, replacing 15 cm of base material with coarse gravel, and setting forms and reinforcing steel. The slabs that remained between the removed sections provided work space for finishing operations. A temporary, propane-heated enclosure (Fig. 2) was erected over one slab as a control section (admixture-free) to provide a comparison between normal and antifreeze concreting operations. An unheated enclosure covered one of the admixture sections as a secondary test. Concrete made with admixtures was placed in the two sections exposed to ambient air outside the shelter and in the section in the unheated shelter.

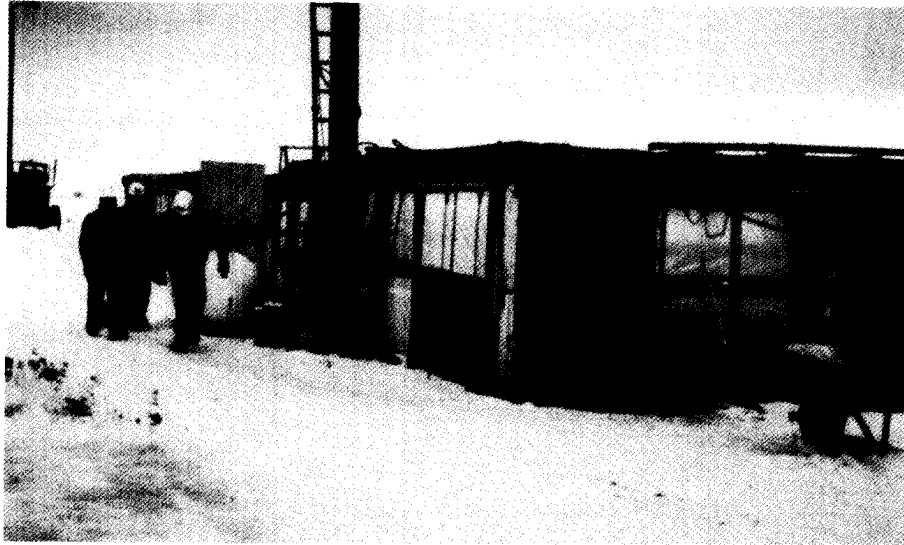


Figure 2. Temporary heated shelter.

Concrete

Two admixtures were tested: the EY11 and DP prototypes. The EY11 admixture was used in two dosages: low and high, designated EY11L and EY11H. The DP admixture was used in a single dosage. Both DP and EY11H were capable of protecting concrete down to -5°C . The EY11L was expected to work down to around -3°C .

Mix	1.9 cm max. size coarse aggregate (kg/m ³)	Sand (kg/m ³)	Type 1A portland cement (kg/m ³)	W/C ratio	Admixture dosage* (%)
Control	1047	774	392	0.41	None
EY11L	1047	774	392	0.41	3.7
EY11H	1047	774	392	0.38	6.3
DP	1047	774	392	0.41	5.2

*Weight active ingredient per cement weight.

Table 2. Concrete placement time.

Mix	Date	Start
Control	15 Mar	11:00 a.m.
EY11L	16 Mar	9:45 a.m.
EY11H	16 Mar	11:40 a.m.
DP	17 Mar	1:10 p.m.

The concrete was transported by rotary-drum truck from a ready-mix plant 8 km from the job site. The concrete was mixed with unheated aggregate and heated water. The ingredients, including all admixtures, were mixed before being

added into the truck (the mix proportions are given in Table 1). Table 2 gives the concrete placement times. The concrete was delivered 30 to 45 minutes after water was added to the mix, and it was placed within another 30 minutes. Consolidation and finishing operations took another 45 to 60 minutes. Table 3 gives the properties of the fresh concrete.

Table 3. Properties of fresh concrete.

Mix	Slump (cm)	Air (%)	Unit wt. (kg/m ³)	Temperature inside the concrete (°C)
Control	5.1	3.2	2307	12.2
EY11L	14	3.2	2307	3.3
EY11H	14	4.7	2275	3.3
DP	12.7	8	2163	7.2

Placing and curing concrete

The concrete for all sections was placed and finished in the normal fashion. No extra effort or skill was required to work outdoors compared to doing the same work inside the heated shelter. The workers found the freedom of movement better outdoors than in the temporary enclosure. The heated shelter was useful as a warming hut between concrete deliveries. The workers stayed outdoors for approximately 2-hour periods. Except for the heated control section, the concrete was thermally unprotected. A plastic sheet was placed over the two exposed concrete sections for 7 days to minimize water loss (Fig. 3). The concrete in the two shelters was uncovered.

Thermal history

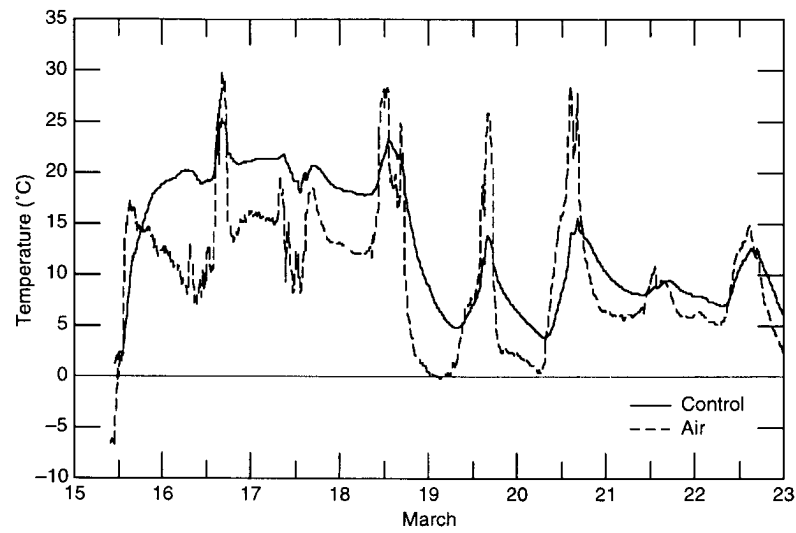
Thermocouples connected to data loggers monitored concrete and air temperatures. Five thermocouples were equally spaced through the

thickness of each slab, beginning at the top surface. An additional thermocouple was positioned away from the concrete, 15 cm above grade and out of direct sunlight, to record the air temperature. For this report only the data from the top surface thermocouples are provided because the top surface was the coolest portion of each slab. It cooled quicker and experienced wider temperature excursions than the rest of the slab, including the bottom surface, which was in contact with the gravel. Figure 4 shows the temperatures of the slabs' top surfaces and the temperature of surrounding air. A separate graph is shown for each concrete section. The recording period for each concrete section began at the time shown in Table 2 and extends through midnight, 22 March. Figure 4 also shows the temperatures from two points near the bottom surface of one slab, and the temperature of one 7.6- × 15.2-cm sample cylinder exposed to the cold.

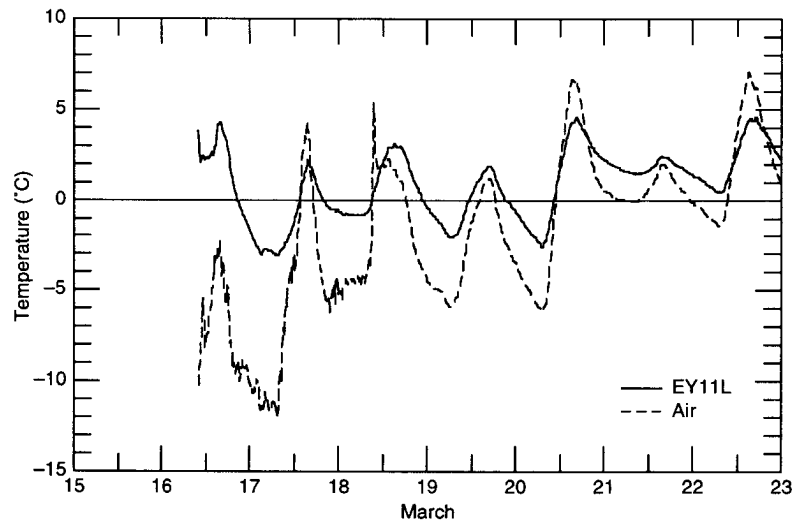
Figure 4a shows the temperatures of the control concrete and the heated air in the shelter. The shelter was heated for several days before 15 March to thaw the frozen ground. To facilitate placement of the control concrete, two walls of the shelter were removed at 10:30 a.m. on 15 March and replaced at noon. The air inside the shelter cooled to -6.6°C by the time concreting started, but, after the walls were replaced, the shelter warmed up again. However, the shelter



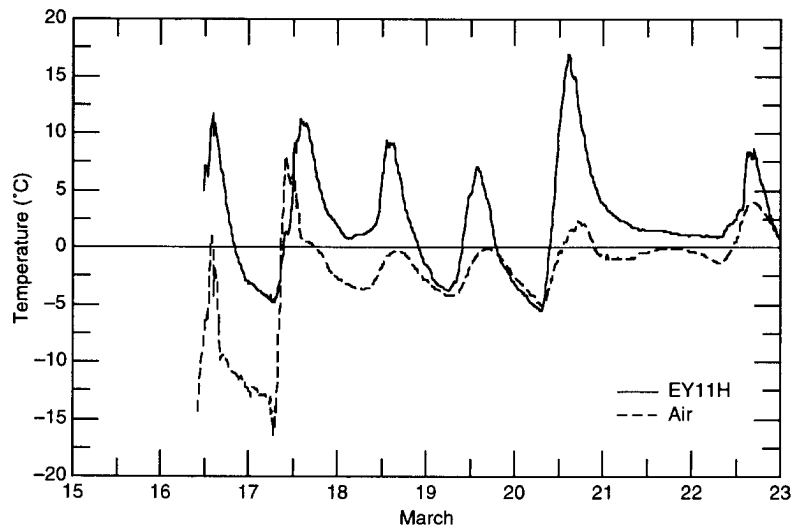
Figure 3. Plastic was placed over the antifreeze concrete cured outdoors.



a. Control concrete and heated air.

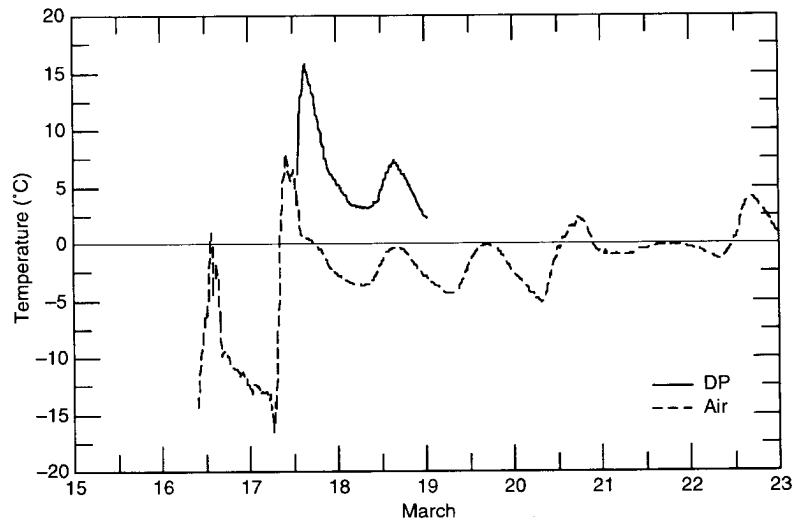


b. EY11L concrete and unheated shelter air.

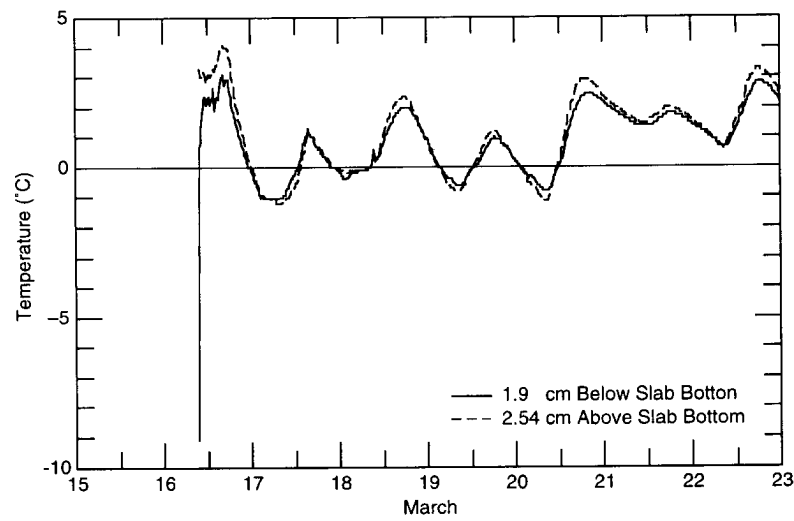


c. EY11H concrete and outside air.

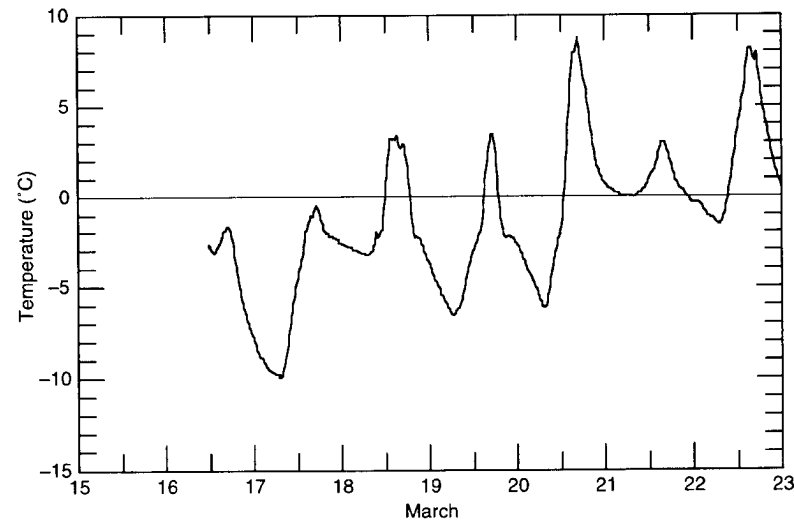
Figure 4. Thermal history of test concretes.



d. DP concrete and outside air.



e. Temperature in gravel and in EY11L slab.



f. Center of EY11L cylinder in unheated shelter.

Figure 4 (cont'd). Thermal history of test concretes.

temperature fluctuated daily. The maximum of 29.7°C occurred at 4:10 p.m. on the 16th, and two lows of -0.2°C and 0.4°C occurred at 3:30 a.m. on the 19th and at 6:45 a.m. on the 20th respectively. The two low temperatures were caused by a malfunction of the heating equipment. The heat was turned off at about 4 p.m. on 22 March. The average air temperature in the shelter for the recording period was 10.5°C.

The control concrete was delivered to the site in two separate shipments, at a temperature of about 12°C for each shipment. (All other concrete was delivered in one truck per section.) By the time both control shipments had been placed and the shelter walls were reinstalled, the concrete had cooled off to 1.3°C (Fig. 4a). It wasn't until 5 p.m. of that same day that the heat supplied by cement hydration and the shelter warmed the concrete to 12°C. The concrete continued to warm until it reached 20.3°C at 7 a.m., 16 March, in spite of the air cooling to 9.4°C. Like the air, the concrete temperature fluctuates throughout the recording period. It reached a maximum temperature of 25.3°C at 4:10 p.m. on the 16th and a minimum of 3.8°C at 7:10 p.m. on the 20th, closely corresponding to the high and low shelter air temperatures. The average temperature of the control concrete through 4 p.m. on 22 March was 13.3°C. It never dropped below zero during this period.

Two of the three antifreeze sections were placed on 16 March, the coldest of the two days that concrete containing antifreeze admixtures was placed. The outdoor air temperature (Fig. 4c and d) through midnight on the 16th averaged -8.7°C, though it rose to slightly above freezing for a short time by midday. The minimum outdoor air temperature of -16.5°C was recorded at 6:45 a.m. on 17 March. Winds created wind chills down to -28°C. Thereafter, the outdoor air temperature became much milder; the average through 4 p.m., 22 March, was -2.4°C.

Figure 4b shows the temperatures of the EY11L concrete and the air inside the unheated shelter. The EY11L mix was placed at 9:45 a.m., 16 March. It was delivered at a temperature of 3.3°C. As was done with the control section, two walls of the unheated shelter were removed temporarily. When exposed to the -10°C (but warming) air, the concrete temperature dropped to 2°C, but almost immediately began rising, reaching 4.3°C by 4 p.m. Then, the concrete temperature dropped to -3°C, its lowest recorded temperature, at 3:30 a.m. on 17 March. This concrete contained a low admixture dosage and had an expected freezing

point of around -3°C. Its average temperature was 0.9°C through 4 p.m., 22 March.

Figure 4c shows the temperatures of the EY11H concrete and the outdoor air. The freezing point of this concrete was -5°C. The EY11H mix was cast outdoors at 11:40 a.m., 16 March. It, too, began at 3.3°C. But, instead of cooling off when exposed to the -7.3°C air, it warmed to 11.8°C at 2:10 p.m., before dropping off to -4.4°C at 7 a.m., 17 March. It reached its lowest temperature of -5.5°C at 7 a.m., 20 March, 4 days after being cast. Its average temperature was 2.4°C through 4 p.m., 22 March.

Figure 4d shows the temperatures of the DP concrete and the outdoor air. The freezing point of this admixture was -5°C. The DP concrete section was cast outdoors at 1:10 p.m., 17 March. It was delivered to the site at 7.2°C, when the air temperature was 4°C and falling. The concrete temperature rose to a high of 15.8°C at 2:30 p.m. on 17 March. Because of a data recorder malfunction, concrete temperatures were not recorded after midnight, 18 March. The average air temperature from the time of placement to midnight, 18 March, was -1.6°C and from placement through 4 p.m., 22 March, was -1°C. The average temperature of the concrete through midnight, 18 March, was 6.3°C. The DP concrete probably did not drop below -5°C through 22 March.

Figure 4e shows the temperatures of two points near the bottom surface of the EY11L slab. The EY11L slab had the lowest average surface temperature of all the slabs. As can be seen in Figure 4e, the bottom surface of the concrete, which was halfway between the two thermocouple positions, could not have frozen. The lowest temperature of the two thermocouples was -1.2°C, 21 hours after the concrete was placed. Recall that the freezing temperature of this concrete was -3°C. The EY11H slab, with a -5°C freezing temperature, experienced the lowest single surface temperature of all the slabs. Its bottom surface temperature reached a low of about -3°C (not shown), 4 days after the concrete was placed.

Figure 4f shows the temperatures of an EY11L cylinder stored on grade in the unheated shelter. The cylinder's temperature dipped below -5°C on several occasions, the first at 8:00 p.m. on 16 March, about 10 hours after it was cast. The average temperature of the cylinder through 4 p.m., 22 March, was -1.3°C.

Strength development

Several 7.6 × 15.2-cm cylindrical samples were cast from each type of concrete and stored in two

locations: on grade next to the slabs, and overhead in the heated enclosure. A concrete testing laboratory (Coleman Engineering Co., Iron Mountain, Michigan) periodically tested the cylinders' compressive strength.

Their compressive strengths cannot be used as an indicator of the in-place strength of the antifreeze concrete because, as Figure 4f shows, the cylinders probably froze. At CRREL, subsequent petrographic analysis of the suspected frozen cylinders revealed typical ice lens patterns. Strengths reported by the testing laboratory indicate that the cylinders developed only about half of their potential strength, which is indicative of concrete that has frozen while curing.

Likewise, the strengths of the cylinders stored overhead in the heated shelter were not considered useful information, other than to confirm that the admixtures promoted strength in concrete cured at above-freezing temperatures. They shed little light on the in-place strength of the concrete slabs.

The most interesting and useful results came from cores drilled from each slab in the summer. The cores showed that the antifreeze concrete was at least as good as the control concrete in compressive strength and appearance. None of the slabs showed signs of frost damage and all of the concrete exceeded minimum design strengths (Table 4). In fact, when it is considered that entrained

Table 4. Test results from 9.2- × 13.3-cm core samples drilled in July 1994.

Mix	Compressive strength* (Mpa)	Bulk density† (g/cm ³)	Evidence of past ice?
Control	46.7	2.31	No
DP	46.0	2.21	No
EY11L	50.6	2.32	No
EY11H	55.5	2.29	No

* Minimum design strength was 32 Mpa.

† Densities based on cylinder dimensions and mass.

air can reduce compressive strength 3% for each 1% of entrained air (U.S. Department of the Interior, Water and Power Resources Service 1981; Kosmatka and Panarese 1988), and that the air contents were generally higher in the admixed concretes than in the control concrete (Table 3), the strength of the admixed concretes exceeded the strength of the control concrete. Though air contents can change when a concrete hardens, the core densities (Table 4) suggest that the concretes retained their relative proportions of air.

Cost comparison

Freeze protection is the primary cost-multiplier of a concrete job done during the winter. Based on the field tests, the main differences between normal winter concreting practice at the Soo and concreting done with antifreeze admixtures are the heat, shelter, and labor needed to protect the normal concrete, and the chemicals in the antifreeze concrete. Table 5 shows an estimate of the relative surcharge, per slab, of each winter concreting method. It is useful to know that the cost of ready-mix concrete at the Soo was \$93.50/m³ the summer before this project and that placement would double this cost.

Table 5. Winter surcharge estimate per slab.

Shelter		Antifreeze	
Erect	\$552	Concrete	5.1 m ³
Materials	\$118	Dosage	97.1mL/kg cement
Heat	\$136	Cement	391 kg/m ³
Dismantle	\$276	Admixture	\$0.80-\$2.10/L
Total	\$1082	Total	\$155-\$407

DISCUSSION

Normal unprotected concrete would have frozen during this test. The freezing-point-depression and accelerated cure properties of the antifreeze concretes enabled them to resist freezing.

The best evidence that the concrete did not freeze was obtained by examining drilled cores. The core samples, taken from each slab 4 months after construction and examined under a microscope, showed no signs of frost damage.

The drilled cores were also tested for compressive strength, which provided additional information that the admixtures produced a concrete that was unaffected by the outdoor winter conditions.

Other than the cold weather, the major concern during the test was that concrete was placed on a subgrade that was significantly below the -5°C protection capability of the admixtures at their highest dosage, let alone at the low dosage. This could mean that the bottom of the concrete would be damaged by frost. Gavrish et al. (1974) reported that up to 16 times more heat is lost from a concrete slab to frozen ground than is lost to the air during initial curing. From our data, however, it was clear that the bottom of the concrete was free from frost damage. The lowest slab-bottom temperature of the low dosage EY11 concrete was about -1.2°C, 21 hours after placement, and for the high dosage EY11 concrete it was -2.6°C, 4

days after placement. At these temperatures and by these times, even admixture-free concrete may have been able to set and become resistant to freezing.

The fact that the antifreeze concrete placed on frozen ground didn't suffer frost damage has implications for normal winter concreting, when placing fresh concrete on frozen ground is prohibited because of the danger of freezing. In this study, when the top surface temperature of the 15-cm slab was above freezing, the bottom surface of the slab did not develop ice. Recall that the concrete was placed on a gravel pad, free of ice. If the concrete had been placed directly on the ground, which contained ice, the situation may have changed because ice can significantly increase heat loss rates. In this case, air spaces among the pieces of gravel probably slowed the heat loss from the slab enough to prevent freezing. Also, the accelerators in the admixture probably provided increased protection through increased heat release during early hydration. More study is needed to test the practice of placing admixture-free concrete on frozen ground.

The test showed that, at times, a plastic sheet provided more than just protection against moisture loss. Figures 4b and c show that the concrete under the plastic sheet was actually warmer than the concrete inside the unheated shelter, at least on sunny days. The sheet-covered concrete was 5 to 10°C warmer during the day on all but 21 March, which was a cloudy day. On that day, the two concrete temperatures were nearly identical. At night, the opposite occurred: the concrete inside the unheated shelter was up to 1.5°C warmer. These observations can be explained by the effect of the large volume of air in the shelter. The plastic sheet, having essentially no air to heat up and cool off, allowed the concrete to heat and cool faster than could the concrete inside the shelter. The 6-day temperature of the concrete under the plastic sheet averaged 2.4°C, vs. 0.9°C for the concrete in the unheated shelter. A blanket of insulation would undoubtedly have performed even more effectively.

Of special interest in these tests was how the work would progress in cold weather. The

workers at the Soo said that working outdoors was much preferred to working in a confining, though heated, enclosure. It was much easier to place and finish the concrete where there was freedom of movement. The consensus was that outdoor concreting was practical down to -20°C, possibly lower, provided a heated shelter was available to warm up in periodically. At the Soo, the personnel worked outdoors in windy -10°C weather for 2-hour intervals. The finishing operation required no special tools, skills or precautions. The antifreeze concrete finished in the same manner as normal concrete. Ice did not build up on the cold metal tools as expected.

Concreting in winter costs more than during the rest of the year. The extra costs in this test were 113% for the enclosure, and up to 43% for the admixture. Costs associated with antifreeze admixtures were more than offset by savings on protection requirements.

From a strength development standpoint, the antifreeze concrete was equal to or better than the concrete placed inside a heated enclosure. Dry heat can create problems. In fact, if the temperature of concrete is not closely regulated, high temperatures can cause significant strength loss, as shown in Figure 1 for the 40°C concrete.

The potential effect on the length of the construction season of being able to place and keep concrete at -5°C, instead of at the current limit of 5°C, can be determined by looking at weather records. The number of days that the maximum air temperature at the Soo exceeded various low temperatures are shown in Figure 5. As can be

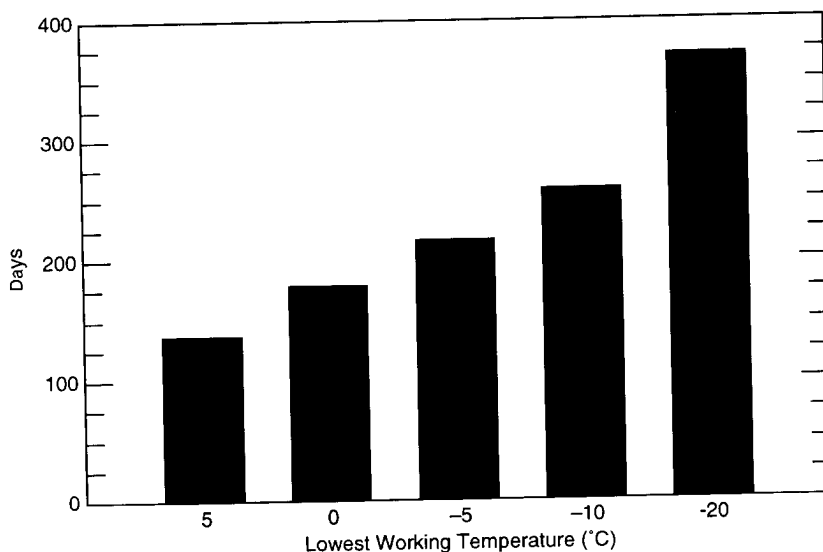


Figure 5. Extension of construction season possible with various low temperature limits (unpublished chart from Horrigan, 1995).

seen, pushing the temperature envelope to -5°C increases the length of the construction season by nearly 80 days. More working days become available at lower temperatures, to the point that concreting is a year-round proposition without the need for heat. The climate at the Soo is similar to that of the coldest areas in the contiguous U.S.

CONCLUSION

The admixtures performed quite well. Data from nearly 2 years of laboratory testing have shown that the prototype admixtures do not harm the concrete and that they are capable of protecting concrete down to -5°C . The field tests clearly demonstrated that working with these new admixtures required no new skills. The concrete was mixed at lower temperatures; the admixture was dosed into the truck, as is normally done with some admixtures today; and the concrete was finished in the usual manner. The major benefit was that, once finished, the concrete was not damaged by exposure to freezing temperatures. The only protection used was a plastic sheet to cover exposed areas to minimize moisture loss during curing. In addition to all of this, a tremendous amount of thermal energy was conserved and the resulting concrete quality was excellent.

The potential effect of being able to place concrete at below-freezing temperatures is significant. Pushing the winter concreting envelope from the current 5°C limit to -5°C can extend the "normal" construction season by around 2 months at the Soo.

Since this field test was conducted, the prototype admixtures have undergone additional research and improvement. Such research will likely produce commercial admixtures that outperform the present prototypes.

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13. ABSTRACT (Maximum 200 words) Two new admixtures, capable of preventing water from freezing, as well as increasing the hydration rate of cement at below-freezing temperatures, were field tested at Sault Ste. Marie, Michigan. Concrete made with the admixtures was placed on a frozen subgrade during a cold winter day and was allowed to cure thermally, unprotected in the cold. Comparison to control concrete placed inside a heated shelter showed that the unprotected, admixed concrete was equal to the control in strength and appearance. Work is continuing on the development of these admixtures for commercial use.					
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